BELLE-CONF-0342

Study of time-dependent CP-violation in $B^0 \to J/\psi\ \pi^0$ decay

K. Abe,[9] K. Abe,[44] N. Abe,[47] R. Abe,[30] T. Abe,[9] I. Adachi,[9] Byoung Sup Ahn,[16] H. Aihara,[46] M. Akatsu,[23] M. Asai,[10] Y. Asano,[51] T. Aso,[50] V. Aulchenko,[2] T. Aushev,[13] S. Bahinipati,[5] A. M. Bakich,[41] Y. Ban,[34] E. Banas,[28] S. Banerjee,[42] A. Bay,[19] I. Bedny,[2] P. K. Behera,[52] I. Bizjak,[14] A. Bondar,[2] A. Bozek,[28] M. Bračko,[21,14] J. Brodzicka,[28] T. E. Browder,[8] M.-C. Chang,[27] P. Chang,[27] Y. Chao,[27] K.-F. Chen,[27] B. G. Cheon,[40] R. Chistov,[13] S.-K. Choi,[7] Y. Choi,[40] Y. K. Choi,[40] M. Danilov,[13] M. Dash,[53] E. A. Dodson,[8] L. Y. Dong,[11] R. Dowd,[22] J. Dragic,[22] A. Drutskoy,[13] S. Eidelman,[2] V. Eiges,[13] Y. Enari,[23] D. Epifanov,[2] C. W. Everton,[22] F. Fang,[8] H. Fujii,[9] C. Fukunaga,[48] N. Gabyshev,[9] A. Garmash,[2,9] T. Gershon,[9] G. Gokhroo,[42] B. Golob,[20,14] A. Gordon,[22] M. Grosse Perdekamp,[36] H. Guler,[8] R. Guo,[25] J. Haba,[9] C. Hagner,[53] F. Handa,[45] K. Hara,[32] T. Hara,[32] Y. Harada,[30] N. C. Hastings,[9] K. Hasuko,[36] H. Hayashii,[24] M. Hazumi,[9] E. M. Heenan,[22] I. Higuchi,[45] T. Higuchi,[9] L. Hinz,[19] T. Hojo,[32] T. Hokuue,[23] Y. Hoshi,[44] K. Hoshina,[49] W.-S. Hou,[27] Y. B. Hsiung,[27,*] H.-C. Huang,[27] T. Igaki,[23] Y. Igarashi,[9] T. Iijima,[23] K. Inami,[23] A. Ishikawa,[23] H. Ishino,[47] R. Itoh,[9] M. Iwamoto,[3] H. Iwasaki,[9] M. Iwasaki,[46] Y. Iwasaki,[9] H. K. Jang,[39] R. Kagan,[13] H. Kakuno,[47] J. Kaneko,[47] J. H. Kang,[55] J. S. Kang,[16] P. Kapusta,[28] M. Kataoka,[24] S. U. Kataoka,[24] N. Katayama,[9] H. Kawai,[3] H. Kawai,[46] Y. Kawakami,[23] N. Kawamura,[1] T. Kawasaki,[30] N. Kent,[8] A. Kibayashi,[47] H. Kichimi,[9] D. W. Kim,[40] Heejong Kim,[55] H. J. Kim,[55] H. O. Kim,[40] Hyunwoo Kim,[16] J. H. Kim,[40] S. K. Kim,[39] T. H. Kim,[55] K. Kinoshita,[5] S. Kobayashi,[37] P. Koppenburg,[9] K. Korotushenko,[35] S. Korpar,[21,14] P. Križan,[20,14] P. Krokovny,[2] R. Kulasiri,[5] S. Kumar,[33] E. Kurihara,[3] A. Kusaka,[46] A. Kuzmin,[2] Y.-J. Kwon,[55] J. S. Lange,[6,36] G. Leder,[12] S. H. Lee,[39] T. Lesiak,[28] J. Li,[38] A. Limosani,[22] S.-W. Lin,[27] D. Liventsev,[13] R.-S. Lu,[27] J. MacNaughton,[12] G. Majumder,[42] F. Mandl,[12] D. Marlow,[35] T. Matsubara,[46] T. Matsuishi,[23] H. Matsumoto,[30] S. Matsumoto,[4] T. Matsumoto,[48] A. Matyja,[28] Y. Mikami,[45] W. Mitaroff,[12] K. Miyabayashi,[24] Y. Miyabayashi,[23] H. Miyake,[32] H. Miyata,[30] L. C. Moffitt,[22] D. Mohapatra,[53] G. R. Moloney,[22] G. F. Moorhead,[22] S. Mori,[51] T. Mori,[47] J. Mueller,[9,†] A. Murakami,[37] T. Nagamine,[45] Y. Nagasaka,[10] T. Nakadaira,[46] E. Nakano,[31] M. Nakao,[9] H. Nakazawa,[9] J. W. Nam,[40] S. Narita,[45] Z. Natkaniec,[28] K. Neichi,[44] S. Nishida,[9] O. Nitoh,[49] S. Noguchi,[24] T. Nozaki,[9] A. Ogawa,[36] S. Ogawa,[43] F. Ohno,[47] T. Ohshima,[23] T. Okabe,[23] S. Okuno,[15] S. L. Olsen,[8] Y. Onuki,[30] W. Ostrowicz,[28] H. Ozaki,[9] P. Pakhlov,[13] H. Palka,[28] C. W. Park,[16] H. Park,[18] K. S. Park,[40] N. Parslow,[41] L. S. Peak,[41] M. Pernicka,[12] J.-P. Perroud,[19] M. Peters,[8] L. E. Piilonen,[53] F. J. Ronga,[19] N. Root,[2] M. Rozanska,[28] H. Sagawa,[9] S. Saitoh,[9] Y. Sakai,[9] H. Sakamoto,[17] H. Sakaue,[31]

T. R. Sarangi,[52] M. Satapathy,[52] A. Satpathy,[9,5] O. Schneider,[19] S. Schrenk,[5] J. Schümann,[27] C. Schwanda,[9,12] A. J. Schwartz,[5] T. Seki,[48] S. Semenov,[13] K. Senyo,[23] Y. Settai,[4] R. Seuster,[8] M. E. Sevior,[22] T. Shibata,[30] H. Shibuya,[43] M. Shimoyama,[24] B. Shwartz,[2] V. Sidorov,[2] V. Siegle,[36] J. B. Singh,[33] N. Soni,[33] S. Stanič,[51,‡] M. Starič,[14] A. Sugi,[23] A. Sugiyama,[37] K. Sumisawa,[9] T. Sumiyoshi,[48] K. Suzuki,[9] S. Suzuki,[54] S. Y. Suzuki,[9] S. K. Swain,[8] K. Takahashi,[47] F. Takasaki,[9] B. Takeshita,[32] K. Tamai,[9] Y. Tamai,[32] N. Tamura,[30] K. Tanabe,[46] J. Tanaka,[46] M. Tanaka,[9] G. N. Taylor,[22] A. Tchouvikov,[35] Y. Teramoto,[31] S. Tokuda,[23] M. Tomoto,[9] T. Tomura,[46] S. N. Tovey,[22] K. Trabelsi,[8] T. Tsuboyama,[9] T. Tsukamoto,[9] K. Uchida,[8] S. Uehara,[9] K. Ueno,[27] T. Uglov,[13] Y. Unno,[3] S. Uno,[9] N. Uozaki,[46] Y. Ushiroda,[9] S. E. Vahsen,[35] G. Varner,[8] K. E. Varvell,[41] C. C. Wang,[27] C. H. Wang,[26] J. G. Wang,[53] M.-Z. Wang,[27] M. Watanabe,[30] Y. Watanabe,[47] L. Widhalm,[12] E. Won,[16] B. D. Yabsley,[53] Y. Yamada,[9] A. Yamaguchi,[45] H. Yamamoto,[45] T. Yamanaka,[32] Y. Yamashita,[29] Y. Yamashita,[46] M. Yamauchi,[9] H. Yanai,[30] Heyoung Yang,[39] J. Yashima,[9] P. Yeh,[27] M. Yokoyama,[46] K. Yoshida,[23] Y. Yuan,[11] Y. Yusa,[45] H. Yuta,[1] C. C. Zhang,[11] J. Zhang,[51] Z. P. Zhang,[38] Y. Zheng,[8] V. Zhilich,[2] Z. M. Zhu,[34] T. Ziegler,[35] D. Žontar,[20,14] and D. Zürcher[19]

(The Belle Collaboration)

[1]*Aomori University, Aomori*
[2]*Budker Institute of Nuclear Physics, Novosibirsk*
[3]*Chiba University, Chiba*
[4]*Chuo University, Tokyo*
[5]*University of Cincinnati, Cincinnati, Ohio 45221*
[6]*University of Frankfurt, Frankfurt*
[7]*Gyeongsang National University, Chinju*
[8]*University of Hawaii, Honolulu, Hawaii 96822*
[9]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[10]*Hiroshima Institute of Technology, Hiroshima*
[11]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*
[12]*Institute of High Energy Physics, Vienna*
[13]*Institute for Theoretical and Experimental Physics, Moscow*
[14]*J. Stefan Institute, Ljubljana*
[15]*Kanagawa University, Yokohama*
[16]*Korea University, Seoul*
[17]*Kyoto University, Kyoto*
[18]*Kyungpook National University, Taegu*
[19]*Institut de Physique des Hautes Énergies, Université de Lausanne, Lausanne*
[20]*University of Ljubljana, Ljubljana*
[21]*University of Maribor, Maribor*
[22]*University of Melbourne, Victoria*
[23]*Nagoya University, Nagoya*
[24]*Nara Women's University, Nara*
[25]*National Kaohsiung Normal University, Kaohsiung*
[26]*National Lien-Ho Institute of Technology, Miao Li*
[27]*Department of Physics, National Taiwan University, Taipei*

[28]H. Niewodniczanski Institute of Nuclear Physics, Krakow
[29]Nihon Dental College, Niigata
[30]Niigata University, Niigata
[31]Osaka City University, Osaka
[32]Osaka University, Osaka
[33]Panjab University, Chandigarh
[34]Peking University, Beijing
[35]Princeton University, Princeton, New Jersey 08545
[36]RIKEN BNL Research Center, Upton, New York 11973
[37]Saga University, Saga
[38]University of Science and Technology of China, Hefei
[39]Seoul National University, Seoul
[40]Sungkyunkwan University, Suwon
[41]University of Sydney, Sydney NSW
[42]Tata Institute of Fundamental Research, Bombay
[43]Toho University, Funabashi
[44]Tohoku Gakuin University, Tagajo
[45]Tohoku University, Sendai
[46]Department of Physics, University of Tokyo, Tokyo
[47]Tokyo Institute of Technology, Tokyo
[48]Tokyo Metropolitan University, Tokyo
[49]Tokyo University of Agriculture and Technology, Tokyo
[50]Toyama National College of Maritime Technology, Toyama
[51]University of Tsukuba, Tsukuba
[52]Utkal University, Bhubaneswer
[53]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[54]Yokkaichi University, Yokkaichi
[55]Yonsei University, Seoul

Abstract

We report a measurement of CP asymmetry parameters in the $b \to c\bar{c}d$-transition-induced decays $B^0(\bar{B}^0) \to J/\psi\ \pi^0$. The analysis is based on a 140 fb^{-1} data sample accumulated at the $\Upsilon(4S)$ resonance by the Belle detector at the KEKB asymmetric-energy e^+e^- collider. We fully reconstruct one neutral B meson in the $J/\psi\ \pi^0$ final state. The accompanying B meson flavor is identified by its decay products. From the distribution of proper time intervals between the two B decays, we obtain the following CP violation parameters:

$$\begin{aligned} \mathcal{S}_{J/\psi\pi^0} &= -0.72 \pm 0.42(\mathrm{stat}) \pm 0.08(\mathrm{syst}) \\ \mathcal{A}_{J/\psi\pi^0} &= -0.01 \pm 0.29(\mathrm{stat}) \pm 0.07(\mathrm{syst}). \end{aligned}$$

PACS numbers:

INTRODUCTION

In the standard model (SM), the Kobayashi-Maskawa (KM) quark-mixing matrix[1] has an irreducible complex phase that gives rise to CP violation in weak interactions. In particular, the SM predicts large CP-violating asymmetries in the time-dependent rates of B^0 and $\bar{B}^0$ decays into a common CP eigenstate f_{CP}[2]. In the decay chain $\Upsilon(4S) \to B^0\bar{B}^0 \to f_{CP} f_{\rm tag}$, where one of the B mesons decays at time t_{CP} to a final state f_{CP} and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\bar{B}^0$, the decay rate has a time dependence given by [3]

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta_t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 + q\cdot\Big[\mathcal{S}_{f_{CP}}\sin(\Delta m_d \Delta t) + \mathcal{A}_{f_{CP}}\cos(\Delta m_d \Delta t)\Big]\Big\}, \tag{1}$$

where τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, $\Delta t = t_{CP} - t_{\rm tag}$, and the b-flavor charge $q = +1$ (-1) when the tagging B meson is a B^0 $(\bar{B}^0)$. The CP-violating parameters $\mathcal{S}_{f_{CP}}$ and $\mathcal{A}_{f_{CP}}$ are given by

$$\mathcal{S}_{f_{CP}} \equiv \frac{2\mathcal{I}m(\lambda)}{|\lambda|^2+1}, \qquad \mathcal{A}_{f_{CP}} \equiv \frac{|\lambda|^2-1}{|\lambda|^2+1}, \tag{2}$$

where λ is a complex parameter that depends on both the B^0-$\overline{B^0}$ mixing and on the amplitudes for B^0 and $\bar{B}^0$ decay to f_{CP}. To a good approximation in the SM, $|\lambda|$ is equal to the absolute value of the ratio of the $\bar{B}^0 \to f_{CP}$ to $B^0 \to f_{CP}$ decay amplitudes.

CP violation in neutral B meson decays involving the $b \to c\bar{c}s$ transition has been established through measurements of the CP-violation parameter $\sin 2\phi_1$ by the Belle [4] and BaBar [5] collaborations. Here, the SM predicts $\mathcal{S}_{f_{CP}} = -\xi_f \sin 2\phi_1$, where $\xi_f = +1(-1)$ corresponds to CP-even (-odd) final states; and $\mathcal{A}_{f_{CP}} = 0$ (or equivalently $|\lambda| = 1$) for both $b \to c\bar{c}s$ and the leading contributions to $b \to c\bar{c}d$ (e.g. the tree diagram). Hence, for $f_{CP} = J/\psi\,\pi^0$, which is a CP-even final state, $\mathcal{S}_{J/\psi\pi^0}$ becomes $-\sin 2\phi_1$ if the tree diagram dominates.

If penguin contributions or other contributions are substantial, a precision measurement of the time-dependent CP asymmetry in $b \to c\bar{c}d$ may reveal values for $\mathcal{S}_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$ that differ from what is expected. Measurements of CP asymmetries in $b \to c\bar{c}d$ transition-induced B decays such as $B^0 \to J/\psi\,\pi^0$ thus play an important role in ascertaining whether or not the KM model provides a complete description of CP violation in B decays.

A study of CP asymmetry in $B^0 \to J/\psi\,\pi^0$ decays has been reported by the BaBar collaboration[7]. In this paper we report a measurement of time-dependent CP violating parameters in $B^0 \to J/\psi\,\pi^0$ decays using the higher statistics data accumulated by the Belle detector.

DATA SAMPLE AND EVENT SELECTION

The results presented here are based on a data sample of 140 fb^{-1} (corresponding to 15.2×10^7 $B\bar{B}$ pairs) collected at the $\Upsilon(4S)$ resonance with the Belle detector [8] at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider [9]. At KEKB, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beamline (z). Since the B^0 and $\bar{B}^0$ mesons are nearly at rest in the $\Upsilon(4S)$ center-of-mass system (cms), Δt can be determined

from the displacement in z between the f_{CP} and $f_{\rm tag}$ decay vertices: $\Delta t \simeq (z_{CP} - z_{\rm tag})/\beta\gamma c \equiv \Delta z/\beta\gamma c$.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5-T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [8].

Hadronic events are selected if they satisfy the following criteria: at least three reconstructed charged tracks; a total reconstructed ECL energy in the center of mass (cms) frame in the range between 0.1 and 0.8 times the total cms energy; an average ECL cluster energy below 1 GeV; at least one ECL shower in the region $-0.7 < \cos\theta < 0.9$ in the laboratory frame; a total visible energy, which is the sum of charged track momenta and total ECL energy, exceeding 0.2 times the total cms energy; and a reconstructed primary vertex that is consistent with the known interaction point. After the imposition of these requirements, the efficiency for selecting B-meson pairs that include a J/ψ meson is estimated by Monte Carlo (MC) simulation to be 99%. To suppress continuum events, we require the event shape variable R_2 to be less than 0.5, where R_2 is the ratio of the second to the zeroth Fox-Wolfram moment [10].

J/ψ mesons are reconstructed via their decay into oppositely charged lepton pairs (e^+e^- or $\mu^+\mu^-$). Leptons are selected by starting with charged tracks satisfying $|dz| < 5$ cm, where dz is the track's closest approach to the interaction point along the beam direction. For electron identification, the ratio between the charged track's momentum and the associated shower energy (E/p) is the most powerful discriminant. Other information including dE/dx, the distance between the ECL shower and the extrapolated track, and the shower shape are also used. Muons are identified by requiring an association between KLM hits and an extrapolated track. Both lepton tracks must be positively identified as such. In the e^+e^- mode, ECL clusters that are within 50 mrad of the track's initial momentum vector are included in the calculation of the invariant mass ($M_{ee(\gamma)}$), in order to include photons radiated from electrons/positrons. The invariant masses of $e^+e^-(\gamma)$ and $\mu^+\mu^-$ combinations are required to fall in the ranges $-0.15 < (M_{J/\psi} - M_{ee(\gamma)}) < +0.036$ GeV/c^2 and $-0.06 < (M_{J/\psi} - M_{\mu\mu}) < +0.036$ GeV/c^2, respectively. Here $M_{J/\psi}$ denotes the world average of the J/ψ mass [14].

Photon candidates are selected from clusters of up to 5×5 crystals in the ECL. Each photon candidate is required to have no associated charged track, and a cluster shape that is consistent with an electromagnetic shower. To select $\pi^0 \to \gamma\gamma$ decay candidates for the $B^0 \to J/\psi\,\pi^0$ mode, the energy of each photon is required to exceed 50 MeV (100 MeV) in the ECL barrel (forward and backward endcap). π^0's are formed from photon pairs that have an invariant mass in the range 0.118 to 0.15 GeV/c^2.

J/ψ and π^0 candidates are combined to select B candidates. The B candidate selection is carried out using two observables in the rest frame of the $\Upsilon(4S)$ (cms): the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - (\sum \vec{p_i})^2}$ and the energy difference $\Delta E \equiv \sum E_i - E_{\rm beam}$, where $E_{\rm beam} = \sqrt{s}/2$ is the cms beam energy, and $\vec{p_i}$ and E_i are the cms three-momenta and energies of the B meson decay products. In this calculation, kinematic fits are performed with (1) vertex and mass constraints for the J/ψ di-lepton decays and (2) mass constraint for the $\pi^0 \to \gamma\gamma$ decays in order to improve the ΔE resolution. Candidate events are selected by

requiring $5.270 < M_{\rm bc} < 5.290$ GeV/c^2 and $-0.10 < \Delta E < 0.05$ GeV. The lower bound of the ΔE requirement is determined in order to accommodate the negative ΔE tail that results from shower leakage associated with the high-momentum π^0. The number of reconstructed $B^0 \to J/\psi\ \pi^0$ candidates is 103. The ΔE and $M_{\rm bc}$ distributions for the candidate events are shown in Fig, 1.

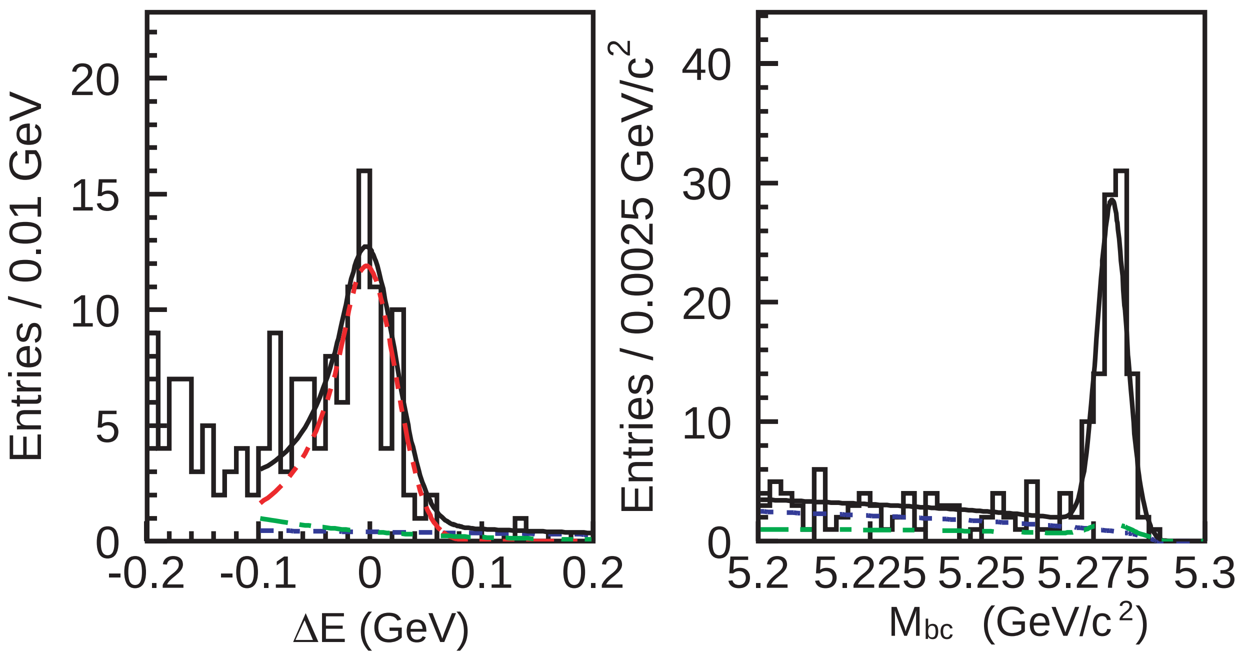

FIG. 1: The ΔE(left) and $M_{\rm bc}$(right) distributions for $B^0 \to J/\psi\ \pi^0$ candidates. The superimposed curves show fitted contributions from signal (red two-dot-dash, plotted only in ΔE distribution), $B \to J/\psi X$ background (green dot-dash), combinatorial background (blue dash) and the sum of all the contributions (black solid). See text for further details.

SIGNAL PROBABILITY

To assign an event-by-event signal probability for use in the maximum-likelihood fit to the CP-violating parameters, we determine event distribution functions in the ΔE-$M_{\rm bc}$ plane for both signal and background. The signal distribution is modeled with a two-dimensional function which is Gaussian in $M_{\rm bc}$ and uses a Crystal Ball line shape [15] in ΔE. The shape parameters of these functions are determined from MC simulation and held fixed in the fit, while the overall signal yield is allowed to float. Backgrounds are studied using a large sample of MC events along with events outside of the signal region. We split the backgrounds into two categories, one being B decays having a $J/\psi(B \to J/\psi X)$ and the other being combinatorial background to which random combinations of particles in $B\bar{B}$ decays and continuum events contribute. According to MC study, the $B \to J/\psi X$ background forms a small peak in the $M_{\rm bc}$ projection. Therefore we parametrize this contribution with the sum of a Gaussian and a phase-space like background function(ARGUS function) [16] in the $M_{\rm bc}$ direction and an exponential function for ΔE. The amount of this background contribution is determined by MC [17]. For the combinatorial background, we use a linear function for ΔE and an ARGUS function for $M_{\rm bc}$. The purity of the signal is estimated to be 86±10%

FLAVOR TAGGING AND VERTEXING

Charged leptons, kaons, pions, and Λ baryons that are not associated with the reconstructed $B^0 \to J/\psi\,\pi^0$ decay are used to identify the b-flavor of the accompanying B meson, denoted by $f_{\rm tag}$. Based on the measured properties of these tracks, two parameters, q and r, are assigned to each event. The first, q, has the discrete value $+1$ (-1) when the tag-side B meson is more likely to be a B^0 ($\bar{B}^0$). The parameter r is an event-by-event MC-determined flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for an unambiguous flavor assignment. It is used only to sort data into six intervals of r, according to the estimated flavor purity. The wrong-tag probabilities for each of these intervals,w_l ($l = 1, 6$), which are used in the final fit, are determined directly from the data samples of B^0 decays to exclusively reconstructed self-tagging channels. The difference of the wrong-tag fractions between B^0 and $\bar{B}^0$ are also determined from the same samples and implemented as $\Delta w_l (l = 1, 6)$ into the final fit. We obtain w_l and Δw_l using time-dependent B^0-$\bar{B}^0$ mixing: $(N_{\rm OF} - N_{\rm SF})/(N_{\rm OF} + N_{\rm SF}) = (1 - 2w_l)\cos(\Delta m \Delta t)$, where $N_{\rm OF}$ and $N_{\rm SF}$ are the numbers of opposite ($B^0\bar{B}^0 \to B^0\bar{B}^0$) and same ($B^0\bar{B}^0 \to B^0 B^0, \bar{B}^0\bar{B}^0$) flavor events. The wrong tag fractions for each r interval are given elsewhere [12].

The decay vertices of B^0 mesons are reconstructed using tracks that have enough SVD hits: i.e. both z and r-ϕ hits in at least one SVD layer and at least one additional layer with a z hit, where the r-ϕ plane is perpendicular to the z (beams) axis. Each vertex position is required to be consistent with the IP profile, which is determined run-by-run and smeared in the r-ϕ plane by 21 μm to account for the B meson decay length. With these requirements, we are able to determine a vertex even in the case where only one track has enough associated SVD hits. The vertex position for the $B^0 \to J/\psi\,\pi^0$ decay is reconstructed using lepton tracks from the J/ψ. The algorithm for the $f_{\rm tag}$ vertex reconstruction is chosen to minimize the effect of long-lived particles, secondary vertices from charmed hadrons and a small fraction of poorly reconstructed tracks [13]. From all the charged tracks with associated SVD hits except those used for $B^0 \to J/\psi\,\pi^0$ reconstruction, we select tracks with a position error in the z direction of less than 500 μm, and with an impact parameter with respect to the J/ψ vertex of less than 500 μm. Track pairs with opposite charges are removed if they have an invariant mass within ± 15 MeV/c^2 of the nominal K_S mass. If the reduced χ^2 associated with the $f_{\rm tag}$ vertex exceeds 20, the track making the largest χ^2 contribution is removed and the vertex is refitted. This procedure is repeated until an acceptable reduced χ^2 is obtained. After flavor tagging and vertex reconstruction, we obtain 91 $B^0 \to J/\psi\,\pi^0$ candidates.

THE UNBINNED MAXIMUM LIKELIHOOD FIT

We determine $\mathcal{S}_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$ for each mode by performing an unbinned maximum-likelihood fit to the observed Δt distribution. The probability density function (PDF) expected for the signal distribution is given by

$$\begin{aligned}
&\mathcal{P}_{\rm sig}(\Delta t, q, w_l, \Delta w_l) \\
&= \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 - q\Delta w_l + q(1-2w_l)\cdot\Big[\mathcal{S}_{f_{J/\psi\pi^0}}\sin(\Delta m_d \Delta t) + \mathcal{A}_{f_{J/\psi\pi^0}}\cos(\Delta m_d \Delta t)\Big]\Big\} \quad (3)
\end{aligned}$$

to account for the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function $R_{\rm sig}(\Delta t)$, which takes into account the finite vertex

resolution. $R_{\rm sig}(\Delta t)$ is formed by convolving four components: the detector resolutions for z_{CP} and $z_{\rm tag}$, the shift in the $z_{\rm tag}$ vertex position due to secondary tracks originating from charmed particle decays, and the kinematic approximation that the B mesons are at rest in the cms [13]. A small component of broad outliers in the Δz distribution, caused by mis-reconstruction, is represented by a Gaussian function $P_{\rm ol}(\Delta t)$. We determine twelve resolution parameters and the neutral- and charged-B lifetimes simultaneously from a fit to the Δt distributions of hadronic B decays and obtain an average Δt resolution of ~ 1.43 ps (rms). We determine the following likelihood value for each event:

$$
\begin{aligned}
&P_i(\Delta t_i; \mathcal{S}_{J/\psi\pi^0}, \mathcal{A}_{J/\psi\pi^0}) \\
&= (1-f_{\rm ol})\int_{-\infty}^{\infty}\Big[f_{\rm sig}\mathcal{P}_{\rm sig}(\Delta t', q, w_l, \Delta w_l)R_{\rm sig}(\Delta t_i - \Delta t') \\
&\quad + f_{\rm bkg}^{J/\psi X}\mathcal{P}_{\rm bkg}^{J/\psi X}(\Delta t')R_{\rm bkg}^{J/\psi X}(\Delta t_i - \Delta t') \\
&\quad + (1 - f_{\rm sig} - f_{\rm bkg}^{J/\psi X})\mathcal{P}_{\rm bkg}^{\rm comb}(\Delta t')R_{\rm bkg}^{\rm comb}(\Delta t_i - \Delta t')\Big]d(\Delta t') + f_{\rm ol}P_{\rm ol}(\Delta t_i)
\end{aligned} \tag{4}
$$

where $f_{\rm ol}$ is the outlier fraction and $f_{\rm sig}$ is the signal probability calculated as a function of ΔE and $M_{\rm bc}$. $\mathcal{P}_{\rm bkg}^{J/\psi X}(\Delta t)$ and $\mathcal{P}_{\rm bkg}^{\rm comb}(\Delta t)$ are the PDFs for $B \to J/\psi X$ and combinatorial background events, respectively. These contributions dilute the significance of CP violation in Eq. (1). They are modeled as a sum of exponential and prompt components, and are convolved with the corresponding resolution functions $R_{\rm bkg}^{J/\psi X}$ and $R_{\rm bkg}^{\rm comb}$, respectively. The resolution functions are modeled by a sum of two Gaussians. All parameters in $\mathcal{P}_{\rm bkg}^{J/\psi X}(\Delta t)$ and $R_{\rm bkg}^{J/\psi X}$ are determined from MC simulation, while the parameters in $\mathcal{P}_{\rm bkg}^{\rm comb}(\Delta t)$ and $R_{\rm bkg}^{\rm comb}$ are determined by a fit to the Δt distribution of a background-enhanced control sample; i.e. events away from the ΔE-$M_{\rm bc}$ signal region. We fix τ_{B^0} and Δm_d at their world-average values [14]. The only free parameters in the final fit are $\mathcal{S}_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$, which are determined by maximizing the likelihood function

$$
\mathcal{L} = \prod_i P_i(\Delta t_i; \mathcal{S}_{J/\psi\pi^0}, \mathcal{A}_{J/\psi\pi^0}) \tag{5}
$$

where the product is over all events.

FIT RESULTS

A fit to the candidate events results in the CP-violation parameters;

$$
\begin{aligned}
\mathcal{S}_{J/\psi\pi^0} &= -0.72 \pm 0.42({\rm stat}) \pm 0.08({\rm syst}) \\
\mathcal{A}_{J/\psi\pi^0} &= -0.01 \pm 0.29({\rm stat}) \pm 0.07({\rm syst}),
\end{aligned} \tag{6}
$$

where the sources of systematic error are given below. Figure 2 shows the Δt distributions for $\bar{B}^0 \to J/\psi\, \pi^0$ (upper figure:$q = +1$) and $B^0 \to J/\psi\, \pi^0$ (lower figure:$q = -1$) event samples. Figure 3 shows the raw asymmetry in each Δt bin without background subtraction, which is defined by

$$
A \equiv \frac{N_{q=+1} - N_{q=-1}}{N_{q=+1} + N_{q=-1}} \tag{7}
$$

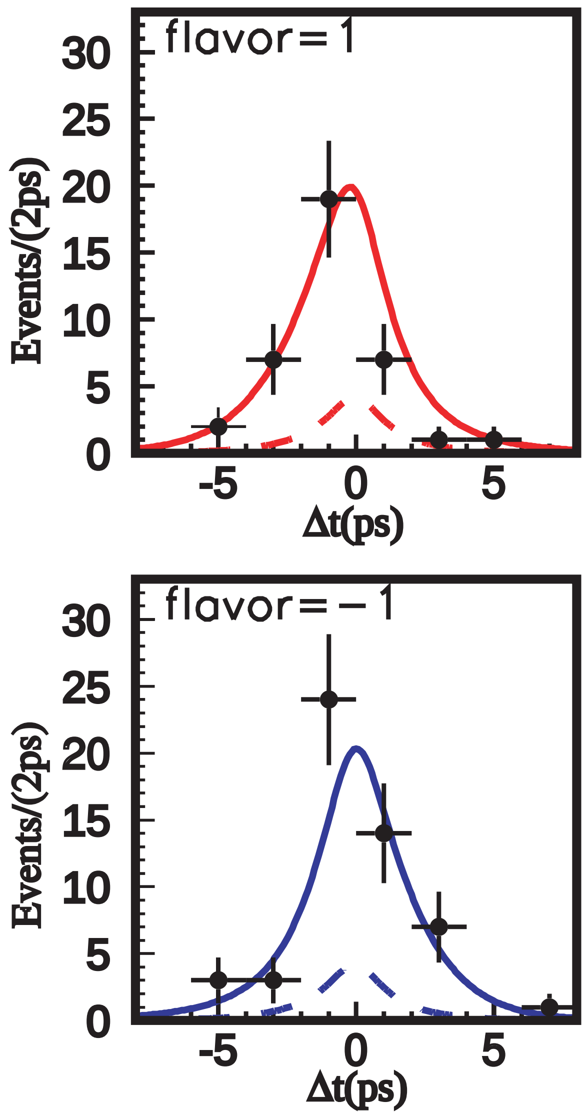

FIG. 2: The Δt distributions for $\bar{B}^0 \to J/\psi\ \pi^0$ (upper:$q = +1$) and $B^0 \to J/\psi\ \pi^0$ (lower:$q = -1$) candidates. The solid curves show the results of the global fits, and dashed curves show the background distributions.

where $N_{q=+1}(N_{q=-1})$ is the number of observed candidates with $q = +1(-1)$. The curve shows the result of unbinned-maximum likelihood fit to the Δt distribution, $\mathcal{S}_{J/\psi\pi^0} \sin(\Delta m_d \Delta t) + \mathcal{A}_{J/\psi\pi^0} \cos(\Delta m_d \Delta t)$.

SYSTEMATIC UNCERTAINTIES

We estimate systematic uncertainties as follows; the flavor tagging (± 0.025 for $\mathcal{S}_{J/\psi\pi^0}$ and ± 0.014 for $\mathcal{A}_{J/\psi\pi^0}$), the signal probability (± 0.023 for $\mathcal{S}_{J/\psi\pi^0}$ and ± 0.016 for $\mathcal{A}_{J/\psi\pi^0}$), the background Δt distribution (± 0.014 for $\mathcal{S}_{J/\psi\pi^0}$ and ± 0.0065 for $\mathcal{A}_{J/\psi\pi^0}$), the resolution function (± 0.010 for $\mathcal{S}_{J/\psi\pi^0}$ and ± 0.0061 for $\mathcal{A}_{J/\psi\pi^0}$), the potential fit bias (± 0.043 for $\mathcal{S}_{J/\psi\pi^0}$ and ± 0.059 for $\mathcal{A}_{J/\psi\pi^0}$), the vertex reconstruction (± 0.062 for $\mathcal{S}_{J/\psi\pi^0}$ and ± 0.018 for

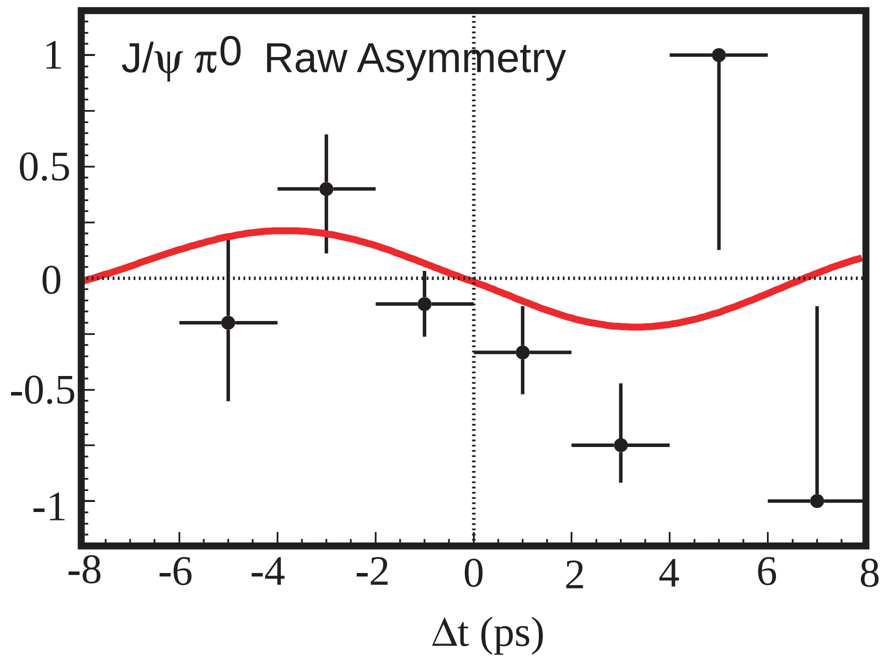

FIG. 3: The Δt asymmetry. The curve shows the result of the unbinned-maximum likelihood fit.

$\mathcal{A}_{J/\psi\pi^0}$), and B meson's lifetime and mixing parameter (± 0.0019 for $\mathcal{S}_{J/\psi\pi^0}$ and ± 0.0071 for $\mathcal{A}_{J/\psi\pi^0}$). The quadratic sum of all the contribution mentioned above amounts ± 0.0845 for $\mathcal{S}_{J/\psi\pi^0}$ and ± 0.0662 for $\mathcal{A}_{J/\psi\pi^0}$.

SUMMARY AND CONCLUSIONS

We have performed a measurement of CP-violation parameters in $B^0 \to J/\psi\ \pi^0$ decay. The resultant values are $\mathcal{S}_{J/\psi\pi^0} = -0.72 \pm 0.42(\mathrm{stat}) \pm 0.08(\mathrm{syst})$ and $\mathcal{A}_{J/\psi\pi^0} = -0.01 \pm 0.29(\mathrm{stat}) \pm 0.07(\mathrm{syst})$. These values are consistent with those obtained for $B^0 \to J/\psi\ K_S$ and other decays governed by $b \to c\bar{c}s$ transition and suggest that penguin and other contributions to this decay mode are not large.

Acknowledgments

We wish to thank the KEKB accelerator group for the excellent operation of the KEKB accelerator. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Industry, Science and Resources; the National Science Foundation of China under contract No. 10175071; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea and the CHEP SRC program of the Korea Science and Engineering Foundation; the Polish State Committee for Scientific Research under contract No. 2P03B 01324; the Ministry of Science and Technology of the Russian Federation; the Ministry of Education, Science and Sport of the Republic of Slovenia; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

* on leave from Fermi National Accelerator Laboratory, Batavia, Illinois 60510

† on leave from University of Pittsburgh, Pittsburgh PA 15260

‡ on leave from Nova Gorica Polytechnic, Nova Gorica

[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[2] A. B. Carter and A. I. Sanda, Phys. Rev. D **23**, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. **B193**, 85 (1981).

[3] A general review of the formalism is given in I.I. Bigi, V.A. Khoze, N.G. Uraltsev, and A.I. Sanda, "CP Violation" page 175, ed. C. Jarlskog, World Scientific, Singapore (1989).

[4] K. Abe *et al.* (Belle Collab.), Phys. Rev. Lett. **87**, 091802 (2001); K. Abe *et al.* (Belle Collab.), Phys. Rev. **D 66**, 032007 (2002); K. Abe *et al.* (Belle Collab.), Phys. Rev. **D 66**, 071102(R) (2002).

[5] BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **87**, 091801 (2001); BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. D **66**, 032003 (2002); BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 201802 (2002).

[6] Throughout this paper, the inclusion of the charge conjugate mode decay is implied unless otherwise stated.

[7] BaBar Collaboration, B. Aubert *et al.*, hep-ex/0303018, submitted to Phys. Rev. Lett.

[8] A. Abashian *et al.* (Belle Collab.), Nucl. Instr. and Meth. A **479**, 117 (2002).

[9] S.Kurokawa and E.Kikutani *et al.* Nucl. Instr. and. Meth. A499, 1 (2003).

[10] G. C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).

[11] A. B. Carter and A. I. Sanda, Phys. Rev. Lett. **45**, 952 (1980); A. B. Carter and A. I. Sanda, Phys. Rev. **D23**, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. **193**, 85 (1981).

[12] K. Abe *et al.*, (Belle Collab.), "Measurement of the CP-Violation parameter $\sin 2\phi_1$ with 152 Million $B^0\bar{B}^0$ pairs." hep-ex/0308036, BELLE-CONF-0353

[13] H. Tajima, H. Aihara, T. Higuchi, H. Kawai, T. Nakadaira, J. Tanaka, T. Tomura, M. Yokoyama (Tokyo U.), M. Hazumi, Y. Sakai, K. Sumisawa (KEK, Tsukuba), T. Kawasaki (Niigata U.). "Proper time resolution function for measurement of time evolution of B mesons at the KEK B factory" hep-ex/0301026, submitted to Nucl. Instr. and Meth. A

[14] Particle Listings in the 2003 Review of Particle Physics. (http://pdg.lbl.gov/2003/cntents_listings.html)
In the likelihood function, we use the following B^0-$\overline{B}^0$-mixing parameter and B meson lifetimes; $\Delta m_d = 0.502 \pm 0.007$ ps^{-1}, $\tau_{B^0} = 1.537 \pm 0.015$ ps^{-1} and $\tau_{B^+} = 1.671 \pm 0.018$ps^{-1}.

[15] A description of this function can be found in Ian C. Brock, BONN-MS-99-02, pp86.

[16] H. Albrecht *et al.* (ARGUS Collab.), Phys. Lett. **B 241**, 278 (1990).

[17] Two-body B meson decays including a J/ψ meson, whose branching fractions are well-measured($B \to J/\psi K^{(*)}$), is dominant contribution. According to MC, $B^0 \to J/\psi\ K_S$ and $B^0 \to J/\psi\ K_L$ decays contribute equally to the peaking background in the $M_{\rm bc}$ projection. They have opposite CP eigenvalues and thus their CP violating contributions cancel.